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(54) Laser with a saturable Bragg reflector

Laser mit einem sättigbaren Bragg-Reflektor

Laser avec un réflecteur de Bragg saturable

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(56) References cited:
- APPLIED PHYSICS LETTERS, 20 MARCH 1989, USA, vol. 54, no. 12, ISSN 0003-6951, pages 1095-1097, XP000097254 KIM B G ET AL: "Nonlinear Bragg reflector based on saturable absorption"
- OPTICS LETTERS, 15 JUNE 1995, USA, vol. 20, no. 12, ISSN 0146-9592, pages 1406-1408, XP000509283 TSUDA S ET AL: "Low-loss intracavity AlAs/AlGaAs saturable Bragg reflector for femtosecond mode locking in solid-state lasers"

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Description

Technical Field

[0001] This invention relates to a semiconductor device and, more particularly, to an intensity dependent reflector for use in modelocking lasers for the generation of ultrashort optical pulses.

Background of the Invention

[0002] Semiconductor saturable absorbers have found applicability as modelocking elements in solid state lasers for generating extremely short duration optical pulses. These pulses are commonly called ultrashort pulses because they exhibit pulse widths in the picosecond and sub-picosecond ranges. Ultrashort optical pulses are useful for high speed signal processing and data communications.

[0003] The saturable absorber allows passive modelocking of a laser when the absorber, which is a nonlinear element, is placed either within the lasing optical cavity or in an optical cavity coupled and external to the lasing cavity. Saturable absorbers act as shutters to incident radiation because they can change their opacity as a function of the intensity of the incident radiation at a particular wavelength. A saturable can absorb all weak incident radiation. As the intensity of incident radiation reaches a sufficiently high level known as the saturation intensity, incident radiation is permitted passage through the saturable absorber. In general, attenuation caused by the absorber is relatively low because the absorber is saturated into a transparent state at the desired wavelength.

[0004] Semiconductor saturable absorbers have been fabricated for narrowband and broadband response. Bulk semiconductor material and multiple quantum well heterostructures have been used for narrowband absorption applications while specially graded bandgap multiple quantum well heterostructures have been developed for broadband applications. In the quantum well realizations of such absorber devices, the quantum well heterostructure has been grown on a semiconductor quarter-wave stack reflector. In another embodiment known as an anti-resonant Fabry-Perot saturable absorber, a thin film oxide partial reflector stack was deposited on the quantum well heterostructure to form a Fabry-Perot etalon with the semiconductor quarter-wave stack reflector. For the latter device, the saturable absorber element (MQW) responds to radiation at wavelengths in the anti-resonant portion of the Fabry-Perot etalon response characteristic. This device attempted to circumvent produce weak coupling with the laser cavity and introduce less loss than other multiple quantum well devices used for modelocking the laser. By the same token, the anti-resonant Fabry-Perot saturable absorber requires significant additional device processing and optimization for its realization.

[0005] Applied Physics Letters vol. 54, pages 1095-1097, 20 March 1989 discloses a Bragg reflector comprising a quarter-wave stack of dielectric layers.

Summary of the Invention

[0006] Low optical loss and simplified fabrication are achieved by a nonlinear reflector which incorporates one or more semiconductor quantum wells within a standard semiconductor quarter wave stack reflector. The nonlinear reflector called a saturable Bragg reflector provides an intensity dependent response which permits it to be used for saturable absorption directly in a main oscillating cavity of a laser. Saturation intensity of the nonlinear reflector and thereby related laser modelocking properties can be controlled by disposing the quantum well at a particular position in the reflector structure.

Brief Description of the Drawing

[0007] A more complete understanding of the invention may be obtained by reading the following description of specific illustrative embodiments of the invention in conjunction with the appended drawing in which:

FIGs. 1 and 2 each show a cross-sectional view of alternative embodiments of the saturable Bragg reflector realized in accordance with the principles of the invention;

FIG. 3 shows a typical reflectivity curve for the saturable Bragg reflector; and

FIG. 4 shows a schematic diagram of a solid state laser including the saturable Bragg reflector as an intracavity element for laser modelocking.

Detailed Description

[0008] The invention is defined in claims 1 and 5. Various embodiments of the invention are defined in the dependent claims.

[0009] The saturable Bragg reflector employs a quarter wave stack dielectric reflector having a high reflectance which, in turn, incorporates one or more quantum wells disposed at predetermined location(s) within the reflector to provide the nonlinear characteristic for the reflector. This structure acts as a low loss saturable absorber which can be utilized directly within the main lasing cavity of a laser such as a solid state laser. Position of the quantum well, along with other factors, determines the saturation intensity of the saturable reflector. This device is grown by molecular beam epitaxy and requires no further processing such as growth, deposition, or oxidation to be ready for use as an intra-cavity saturable absorber.

[0010] The illustrative embodiments of the invention shown in FIGs. 1 and 2 employ a single quantum well grown within the reflector structure. These devices are

shown on a GaAs substrate 14 with layers formed in the AlAs/AlGaAs semiconductor compound system for illustrative purposes only.

[0011] In each device, the Bragg reflector comprises a series of alternating material layers having different refractive indices. It can also be viewed as a plurality of pairs of layers wherein each pair 10 of layers includes one wide energy bandgap layer and one narrow energy bandgap layer. When the layers are arranged with individual layer thicknesses approximating a quarter wavelength (one quarter of an optical path length), the stack of layers will fom a mirror of reflectivity approaching unity. As shown in the FIGs., thirty to forty pairs of AlAs/AlGaAs layers form the reflector. The mole fraction x for the compound $AlGa_{1-x}As_x$ is varied between 1.0 in the wide bandgap AlAs layers 13 to 0.15 in the narrow bandgap AlGaAs layers 12. This system of layers is suitable for operation in the wavelength range around 850 nm. Since the reflector is a standard quarter wave stack design, the optical thickness of each layer should be approximately one-quarter of the desired wavelength of operation. The reflector alone without the quantum well exhibits an intensity independent reflectivity and, if placed in a laser cavity, will not influence or induce modelocking.

[0012] A single quantum well 11 provides saturable absorption, that is, intensity dependent absorption which is required for modelocking. The quantum well is grown near the top surface of the reflector (FIG. 2) when a low saturation intensity is desired; it is grown farther from the top surface of the reflector (FIG. 1) when a high saturation intensity is desired. Experimental results now show that high quality modelocking results occur when the quantum well is placed within the first quarter wave thick layer of the reflector where the intensity of the incident radiation is very high. The quantum well can be placed at other locations within the reflector. Additional quantum wells can be disposed within the reflector to obtain a particular saturation characteristic. In addition, the quantum wells can have differing thicknesses or bandgap energies to affect the range (bandwidth) of the saturation effect.

[0013] Since the quantum well interacts with the standing wave pattern of the optical signal, placement of the quantum well at a specific location within selected pair of layers also affects the saturation intensity. Optical field penetration within the reflector is shown over the layers in FIG. 2. It is considered desirable, though not limiting, to place the quantum well near an intensity peak in the standing wave pattern.

[0014] Insertion of the quantum well or quantum wells within the reflector in no way changes the nature of the mirror from being a single, high reflectance reflector. The Bragg reflector, even though its structure is briefly interrupted by the quantum well, is still a single reflector and not an etalon or cavity reflector. The maximum reflectance of the saturable Bragg reflector in experimental practice is approximately 99.8% as shown by curve 31 in FIG. 3. The presence of the quantum well modifies the reflection (absorption) characteristic of the saturable Bragg reflector near the exciton wavelength marked with an x and arrow 32.

[0015] As shown in the FIGs., the quantum well layer is grown in the narrow bandgap AlGaAs layer. The mole fraction x for the quantum well is chosen so that the excitons are confined to a state below the bandgap of the narrow bandgap layers in the Bragg reflector. In the example from experimental practice, a mole fraction less than 0.15 is suitable for use. A quantum well thickness of approximately 100Å (1 nm = 10Å) has been used in the experimental device with an exciton wavelength of approximately 850 nm.

[0016] It has been discovered that the thickness of the reflector layer which includes the quantum well can be maintained at its standard quarter wave thickness diminished by the quantum well thickness without any significant change in performance. That is, there is no need to a first approximation to account for the actual change in optical path length caused by the presence of the quantum well in the reflector layer. As such, the total thickness of the reflector layer together with the quantum well layer can be approximated with sufficiently good results by the quarter wave thickness of a standard reflector layer of the same material type without the quantum well.

[0017] FIG. 4 shows the saturable Bragg reflector (SBR) within the main cavity of a Ti:Sapphire laser for the purpose of modelocking the laser. Ti:Sapphire rod 46 (3mm long) is pumped by argon laser 48. The Ti:Sapphire rod provides optical gain for the modelock laser. Lens 47 is used for coupling the pump beam into the optical cavity. The main laser cavity is formed between high reflectivity mirror 41 and the saturable Bragg reflector 49. Mirrors 44 and 45 are used for directing the optical signals through rod 46 as the gain medium. Brewster prisms 42 and 43 provide adjustable negative and positive dispersion which is used for pulse shaping. The saturable Bragg reflector is placed substantially at the focal point of 20 cm radius curved mirror 50. Output coupling of the optical pulses produced by the laser is provided through mirror 50. The laser spectrum is shown as curve 33 in FIG. 3.

[0018] Saturation of the saturable Bragg reflector modelocks the laser in FIG. 4 which produces a modelock sequence of optical pulses. Pulsewidth is determined by dispersion and bandwidth limiting properties of the saturable Bragg reflector. The arrangement shown in FIG. 4 has been used to generate ultrashort optical pulses having a pulse autocorrelation of approximately 90 fs.

[0019] The saturable Bragg reflector realized in experimental practice exhibited a reflectivity which was not flat over the band of interest as a result of systematic errors which occurred during MBE growth. This is shown in FIG. 3. If the saturable Bragg reflector were made with a flat-topped reflectivity spectrum over the band of in-

terest, larger modelock bandwidths could be attained. In addition, such a feature would be useful for tuning the laser.

[0020] It should be noted that the dispersion compensation provided by the Brewster prisms 42 and 43 can be removed from the laser cavity. In this case, pulsewidths of approximately 5 ps can be obtained from the laser. Self-starting for the modelocking process is readily obtained because the saturation nonlinearity is based upon energy of the incident radiation, not its intensity. As a result, the use of the saturable Bragg reflector in modelock lasers is advantaged over modelock lasers employing pure Kerr lenses.

[0021] It is contemplated that the quantum wells can be grown at low temperature to produce a short response time for the device. It is understood that, while the Group III-V material system AlAs/AlGaAs is described above for fabricating the saturable Bragg reflector, other material combinations may be selected from other semiconductor Group III-V systems such as GaAs/InGaAs, InGaAs/InGaAlAs, InGaAs/InAlAs, GaAs/AlAs, GaAsSb/GaAlAsSb and InGaAsP/InP to realize the device. In these semiconductor systems, the layers may be lattice-matched to suitable GaAs or InP substrates. Mismatching is also contemplated wherein strained layers are grown over the substrate material. Finally, extension of the device structures to semiconductor compounds in Group II-VI and Group IV is also contemplated.

Claims

1. A laser for generating an optical beam at a wavelength comprising first (41) and second (49) end reflectors and a gain medium, said second end reflector (49) including a quarter-wave stack of dielectric material layers (11,12,13) and a quantum well layer (11) within one of said layers in the quarter wave stack so that said second end reflector (49) provides a nonlinear saturation response to incident radiation in order to modelock said laser.

2. The laser as defined in claim 1 wherein the quarter-wave stack (11,12,13) comprises a plurality of alternately wide and narrow bandgap semiconductor material.

3. The laser as defined in claim 2 wherein the quantum well (11) is located in a first layer of said quarter wave stack (11,12,13).

4. The laser as defined in claim 3 wherein the wide bandgap layers comprise AlGaAs (12) and the narrow bandgap layers comprise AlAs (13).

5. A dielectric mirror comprising a quarter-wave stack of dielectric material layers (11,12,13) and a quantum well layer (11) within one of said layers in the quarter wave stack so that said dielectric mirror provides a nonlinear saturation response to incident radiation.

6. The laser as defined in claim 5 wherein the quarter-wave stack (11,12,13) comprises a plurality of alternately wide and narrow bandgap semiconductor material.

7. The laser as defined in claim 6 wherein the quantum well (11) is located in a first layer of said quarter wave stack (11,12,13).

8. The laser as defined in claim 7 wherein the wide bandgap layers comprise AlGaAs (12) and the narrow bandgap layers comprise AlAs (13).

Patentansprüche

1. Laser zum Erzeugen eines Lichtstrahls mit einer Wellenlänge, umfassend einen ersten (41) und zweiten (49) Endreflektor und ein Verstärkungsmedium, wobei der zweite Endreflektor (49) einen Satz von λ/4-Schichten aus dielektrischen Materialschichten (11, 12, 13) und eine Quanten-Well-Schicht (11) innerhalb einer der Schichten in dem Satz von λ/4-Schichten enthält, so daß der zweite Endreflektor (49) auf einfallende Strahlung ein nichtlineares Sättigungsverhalten aufweist, um die Betriebsart des Lasers zu synchronisieren.

2. Laser nach Anspruch 1, bei dem der Satz von λ/4-schichten (11, 12, 13) mehrere Materialien mit abwechselnd breiten und schmalen Bandabständen umfaßt.

3. Laser nach Anspruch 2, bei dem der Quanten-Well (11) in einer ersten Schicht des Satzes von λ/4-Schichten (11, 12, 13) angeordnet ist.

4. Laser nach Anspruch 3, bei dem die Schichten mit breitem Bandabstand AlGaAs (12) und die Schichten mit schmalem Bandabstand AlAs (13) umfassen.

5. Dielektrischer Spiegel, der einen Satz von λ/4-Schichten (11, 12, 13) aus dielektrischem Material und eine Quanten-Well-Schicht (11) innerhalb einer der Schichten in dem Satz aus λ/4-schichten enthält, so daß der dielektrische Spiegel für einfallende Strahlung ein nichtlineares Sättigungsverhalten aufweist.

6. Laser nach Anspruch 5, bei dem der Satz von λ/4-schichten (11, 12, 13) mehrere Materialien mit abwechselnd breiten und schmalen Bandabständen

umfaßt.

7. Laser nach Anspruch 6, bei dem der Quanten-Well (11) in einer ersten Schicht des Satzes von λ/4-Schichten (11, 12, 13) angeordnet ist.

8. Laser nach Anspruch 7, bei dem die Schichten mit breitem Bandabstand AlGaAs (12) und die Schichten mit schmalem Bandabstand AlAs (13) umfassen.

Revendications

1. Laser destiné à générer un faisceau optique à une certaine longueur d'onde, comprenant des premier (41) et deuxième (49) réflecteurs terminaux et un milieu de gain, ledit deuxième réflecteur terminal (49) comportant un empilement quart d'onde de couches de corps diélectrique (11, 12, 13) et une couche à puits quantique (11) dans l'une desdites couches dans l'empilement quart d'onde, de sorte que ledit deuxième réflecteur terminal (49) fournisse une réponse de saturation non linéaire vis-à-vis du rayonnement incident afin de synchroniser les modes dudit laser.

2. Laser selon la revendication 1, dans lequel l'empilement quart d'onde (11, 12, 13) comprend une pluralité de corps semiconducteurs à bande interdite alternativement large or étroite.

3. Laser selon la revendication 2, dans lequel le puits quantique (11) est situé dans une première couche dudit empilement quart d'onde (11, 12, 13).

4. Laser selon la revendication 3, dans lequel les couches à bande interdite large comprennent de l'AlGaAs (12) et les couches à bande interdite étroite comprennent de l'AlAs (13).

5. Miroir diélectrique comprenant un empilement quart d'onde de couches de corps diélectrique (11, 12, 13) et une couche à puits quantique (11) dans l'une desdites couches dans l'empilement quart d'onde, de sorte que ledit miroir diélectrique fournisse une réponse de saturation non linéaire vis-à-vis du rayonnement incident.

6. Laser selon la revendication 5, dans lequel l'empilement quart d'onde (11, 12, 13) comprend une pluralité de corps semiconducteurs à bande interdite alternativement large et étroite.

7. Laser selon la revendication 6, dans lequel le puits quantique (11) est situé dans une première couche dudit empilement quart d'onde (11, 12, 13).

8. Laser selon la revendication 7, dans lequel les couches à bande interdite large comprennent de l'AlGaAs (12) et les couches à bande interdite étroite comprennent de l'AlAs (13).

FIG. 1

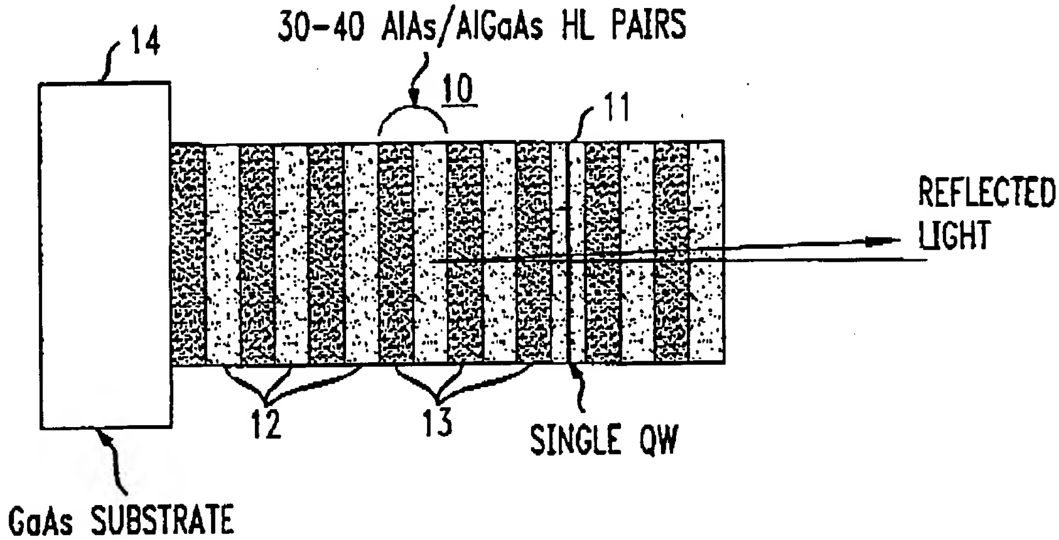

30-40 AlAs/AlGaAs HL PAIRS
14
10
11
REFLECTED
LIGHT
12
13
SINGLE QW
GaAs SUBSTRATE

FIG. 2

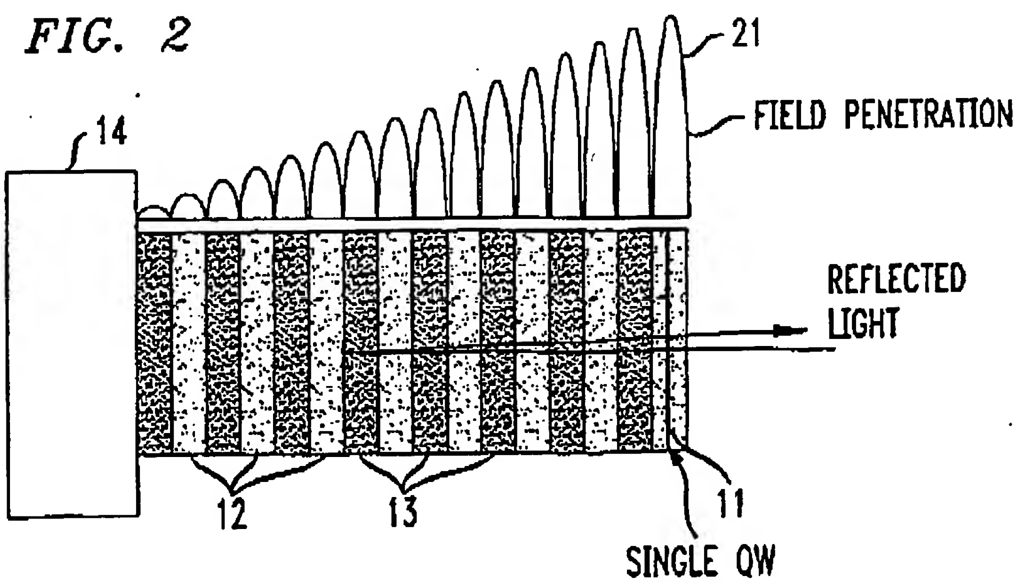
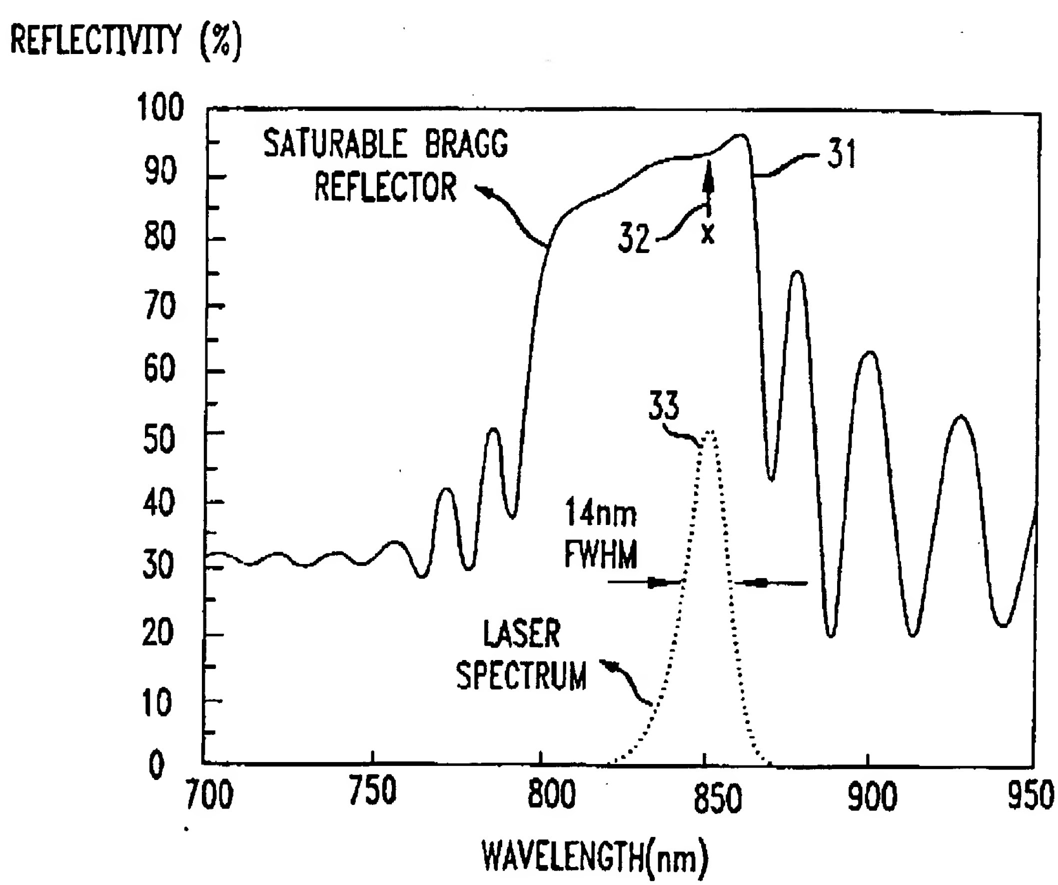

21
FIELD PENETRATION
14
REFLECTED
LIGHT
12
13
11
SINGLE QW

FIG. 3


REFLECTIVITY (%)
100
90
80
70
60
50
40
30
20
10
0
SATURABLE BRAGG REFLECTOR
31
32
x
33
14nm FWHM
LASER SPECTRUM
700
750
800
850
900
950
WAVELENGTH(nm)

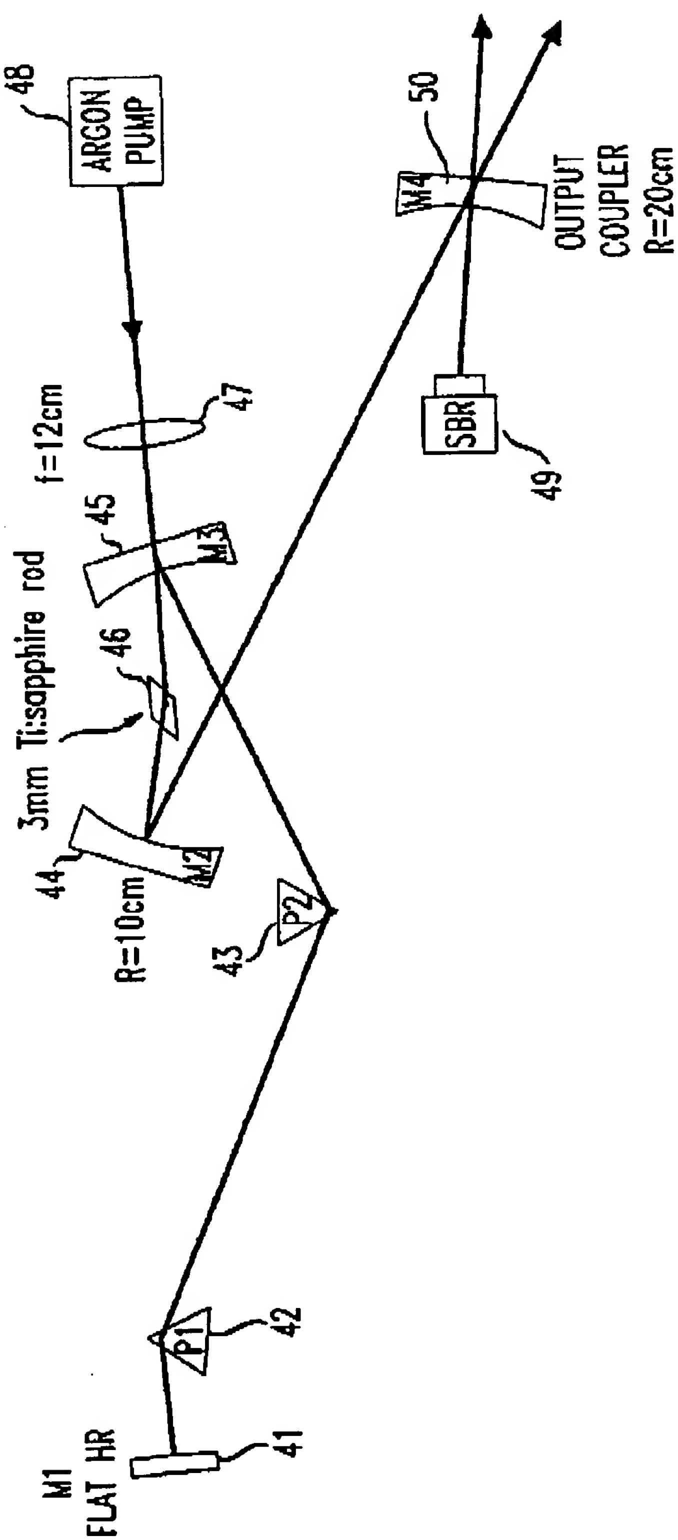

ARGON PUMP
48
50
M4
OUTPUT COUPLER R=20cm
f=12cm
47
SBR
49
45
M3
3mm Ti:sapphire rod
46
44
M2
R=10cm
P2
43
P1
42
41
M1 FLAT HR

FIG. 4

